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High-z Galaxies Detected by the GOODS IRAC Observations in the *HST* Ultra Deep Field

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Abstract. The first epoch of Infrared Array Camera (IRAC) observations of the Great Observatories Origins Deep Survey (GOODS) *Spitzer* Legacy Program have successfully detected galaxies out to $z \approx 6$, allowing us to study the rest-frame optical properties of galaxies at these very high redshifts. We investigate such properties of a collection of Lyman-break galaxy candidates at z=5–6 in the Hubble Ultra Deep Field (HUDF), several of which have spectroscopic confirmations. We find that the bulk of the rest-frame optical fluxes of these IRAC-identified high-redshift galaxies are best fitted by well-evolved stellar populations with stellar masses of a few $\times 10^{10} M_{\odot}$ and ages of a few hundred million years. This implies that massive galaxies already existed when the universe was only ~ 0.9 Gyr old, and that the formation redshifts of their evolved components could be as early as at $z_f \approx 10$–11. These evolved populations can be well explained by a single stellar population, suggesting that they were formed through a sudden on-set rather than a prolonged process. Their colors are consistent with solar metallicity, suggesting that they might already have been significantly polluted by metals.

1. GOODS IRAC CDF-S Observations and the Identifications of $z \approx$ 5–6 Objects in the HUDF

The IRAC data used here are the mosaics of the first epoch of GOODS observations of the CDF-S. The HUDF is covered in all four IRAC channels with a nominal exposure time of ~ 23.18 hours per pixel. The final drizzle-combined mosaics have a pixel scale of $0.6''$ (see Yan et al. 2004). The $z \approx 6$ sample is from the HUDF i_{775}-band dropout sample of Yan & Windhorst (2004), while the $z \simeq 5$ sample is from the V_{606}-band dropout sample of Yan et al. (in preparation). Three $z \approx 6$ objects and twelve $z \approx 5$ objects have found secure IRAC counterparts, all of which have their IRAC centroids within $0.6''$ from the centroids as measured in the ACS images. All the three $z \approx 6$ and four of the twelve $z \approx 5$ objects also have NICMOS HUDF measurements. One of the $z \approx 6$ objects has spectroscopic redshift of $z = 5.83$ (e.g., Dickinson et al. 2004), and one has been confirmed by the ACS Grism observations to be at $z = 6.0 \pm 0.2$ (Malhotra et al. 2005, submitted to ApJ). Three of the $z \approx 5$ objects have also been spectroscopically confirmed (Stern et al., in preparation).

2. Color Diagnosis and SED Analysis

Rest-frame UV colors of these objects show that they are all very blue, some of which are even bluer than the most metal-poor, zero-age models of Bruzual & Charlot (2003). This indicates that dust reddening (but not necessarily dust extinction) for most of these objects are likely negligible. Meanwhile, their rest-frame UV-to-optical colors indicate that they are consistent with having solar metallicities. Lower metallicities would make the estimated ages older, in some cases even older than the age of the universe at the observed redshifts. We find that a short-duration star formation process is preferred while interpreting their SEDs, as a longer duration would yield an older age and a higher stellar mass. Furthermore, most of these objects (but not all) require the presence of a well-evolved component as well as a young component. The representative examples of the SED analysis are shown Fig. 1, with the estimates of ages and stellar masses labeled. All these objects have an evolved population with an age to the order of a few hundred million years and a stellar mass to the order of a few $\times 10^{10} M_{\odot}$. These results suggest that massive galaxies were already in place when the universe was as young as ~ 0.9 Gyr.

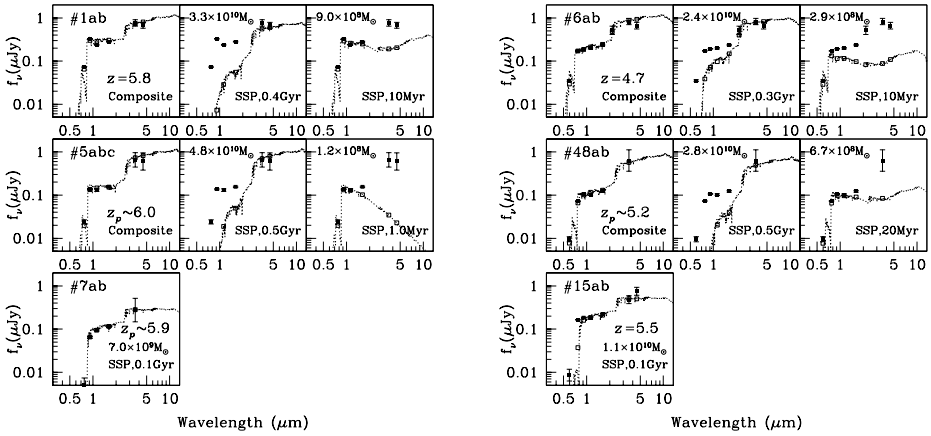

Figure 1. Representative examples of the SED fitting for $z \approx 6$ (left) and $z \approx 5$ (right). The template spectra (curves) are from Bruzual & Charlot (2003). The filled squares are observed values, while the open squares are the simulated values using the templates. Most of these objects need a combination of a major, well-evolved population and a secondary, young component to explain their SEDs (see top and middle rows).

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References

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